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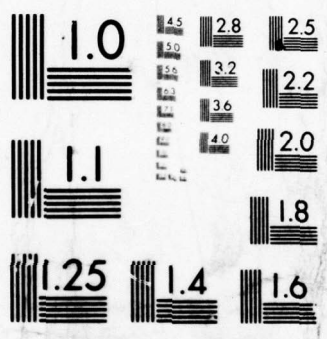
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FINAL REPORT R-BT 378

BERYLLIUM-TITANIUM MATERIALS OPTIMIZATION PROGRAM

by George H. Keith
March 17, 1978

Department of the Navy
Naval Air Systems Command
Washington, D.C. 20361

Contract N-00019-76-C-0355



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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Be/Ti alloy composites were developed having high tensile yield strength/proportional limit (≥ 40 ksi), 28×10^6 psi modulus and 3.32 g/cc density. Composite rods containing 133 and 259 filaments were tested containing filaments made from 4 grades of beryllium: P-1, HIP 50, HIP 70, and HP 40. The best combination of tensile yield strength/proportional limit and ductility was achieved using HIP 70 beryllium.		

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FINAL REPORT

BERYLLIUM-TITANIUM MATERIALS OPTIMIZATION PROGRAM

Preface: This final technical report is submitted in accordance with the requirements of Contract N-00019-76-C-0355. This report details the work from May 28, 1976 to December 28, 1977. This contract was under the technical direction of Mr. W. T. Highberger, Department of Navy, Naval Air Systems Command, Washington, D.C.

Background: In a previous program Be-Ti composites clad in titanium were produced for fabrication by isothermal forging into prototype fan blades for evaluation. This evaluation conducted by Spees¹ et al, was conducted on both powder-powder and filamentary type composites. After preliminary evaluation, the filamentary type composite was chosen for further characterization by measurement of creep properties, high and low cycle fatigue properties, and high impact tolerance. As a result of that program it was recommended that additional work on both powder-powder and filamentary composites was needed.

With this background in mind the program reported here was implemented. Although two powder composites were included, the main emphasis was placed on the filamentary composite particularly using the newer grades of Be. The materials to be produced and evaluated were the actual composites themselves - not Ti alloy clad composites.

Objective: This program was conducted for the purpose of developing a

¹Optimization and Design Criteria for Beryllium/Titanium Composites, J. A. Spees, R. W. Stusrud, G. R. Sippel, M. Herman, Detroit Diesel Allison Division, General Motors Corporation for Department of the Navy, September 1975.

material/process combination which would result in the production of a high quality Be-Ti composite with an improved proportional limit. The aim was a proportional limit of approximately 275 MPa (40 ksi). The density of approximately 3.2 g/cc (.11 lbs/in³) and elastic modulus of about 195 GPa (28×10^6 psi) were fixed by holding the volume fraction at 50%. The titanium alloy used throughout was also fixed at Ti-6Al-4V.

Procedure: The program consisted of two phases; a filamentary composite produced using four different grades of Be (Phase I) and a powder-powder composite produced using two different grades of Be (Phase II). Emphasis was placed on the Phase I filamentary composites and, in particular, on the newer grades of Be. The production of these two types of composite, described below, is summarized in Figures 1 and 2.

A. Production of starting materials Phase I - The three newer grades of Be were all produced using a single lot of $-44 \mu\text{m}$ P-1 powder. Material "A" was produced by sieving to $-37 \mu\text{m}$ and hot isopressing. Material "B" was produced by air classifying to $-20 \mu\text{m}$ and hot isopressing. Material "C" was produced by ball milling and air classifying to $-15+5 \mu\text{m}$ and hot isopressing. The commercial grade, material "D", was purchased directly from the KBI, Hazleton plant as hot pressed block (HP-40). All four materials were machined to $3.5'' \text{ } \varnothing \times 10''$ long. Chemical analyses of these materials are given in Table 1 and tensile properties in Table 2. The four Ti-6-4 alloy tubes were purchased directly from an outside vendor. Their chemistries are included in Table 3.

B. Production of starting materials Phase II - The two powder-powder composites were produced by sieving, blending, and hot isopressing the

50/50 vol. % blends. The only difference was the chemistry of the starting Be chip (Table 1). The Ti-6-4 powder was produced by the rotating electrode process (REP) and was purchased from an outside vendor. (Chemistry in Table 3.)

C. Extrusion Phase I - Production of the filamentary composites was accomplished by a series of four extrusion campaigns (Figure 3). All extrusions were contained in mild steel which was flame sprayed with copper to improve lubricity. Those extrusions which produced a bond (Be-Ti in campaign 1, Ti-Ti in campaigns 3, 4) were evacuated and sealed prior to extrusion. Because of the extremely high extrusion constants measured (415-480 MPa) (30-34.7 TSI) and the attendant risk of stalling the extrusion press, the extrusion temperature was maintained at 705°C (1300°F) except in the final campaign where billets were extruded at both 705°C (1300°F) and 650°C (1200°F). In that campaign extrusion of material A composite was also attempted at 540°C (1000°F) but stalled the press. Extrusion constants for all campaigns are given in Table 4 and macrographs of the composites produced in Figure 4.

D. Extrusion Phase II - Production of the powder-powder composites was accomplished in a single extrusion campaign (Figure 2). The approximately 95% dense HIP billets were encapsulated in mild steel cans flame sprayed with copper to improve lubricity. Billets 76033 and 76034 (HP-40 chip) both stalled the press at an attempted reduction ratio of 13:1 but were successfully extruded at the lower reduction ratio of 9:1. Billets 76031 and 76032 (P-1 chip) were both extruded 13:1 at 705°C (1300°F) since billet 76031 required 1720 of the available 1750 tons. Lowering the extrusion temperature to 650°C (1200°F) would probably have resulted in stalling the press.

An attempt was made to re-extrude these powder-powder composites 2:1 at 540°C (1000°F). However, the composite was so stiff that it acted as a man-

drel and the mild steel billet encapsulating it extruded as a hollow tube without reduction in diameter of the composite. Extrusion constants measured in this phase are included in Table 4.

E. Evaluation of materials produced - Most data was obtained on tensile specimens of the type shown in Figure 5. This specimen (standard in the Be industry) has a .124" gage diameter and a .5" gage length. The strain is measured by a clip-on extensometer at a magnification ratio of 1000:1. For the larger diameter composites (259 filaments), tensile data was also obtained on a larger specimen with the same geometry but having a .250" gage diameter and a 1" gage length. Strain was measured by two techniques:

- a) clip-on extensometer, 1" gage length
- b) bonded strain gage type MM EA-06-125 BZ-350

Elevated temperature (600°F) tensile data were obtained only on the larger specimen since the temperature limit for the 1/2" extensometer is 400°F.

Although Young's Modulus was estimated from the flow curves of all tests, precision measurements were made only on the large specimens using bonded strain gages.

It must be recognized that measurement of the proportional limit is extremely difficult. The ASTM notes² that the values observed for the p.l. vary greatly with the sensitivity and accuracy of the testing equipment, excentricity of loading, the scale to which the stress strain curves

²ASTM Standard E 6-66 Section 25 and
ASTM Standard E 8-69 Par. 5.3.1.1 note 14

are plotted as well as other factors. The p.l. is the highest stress for which the offset is not measurable with the instrument used. A much more accurate estimate of the true p.l. is achieved by measuring the stress at some offset. Therefore, included in the data are the .01% offset strengths for the materials of interest; these were measured as stated above. It should be noted that the effective magnification ratio of the bonded strain gages is ~31500:1.

Densities (Table 5) were determined by an immersion technique and volume percent Be calculated from the density. Volume percent Be was also calculated based on average measured diameter of the individual Be fibers compared with composite diameter.

Standard Be metallographic techniques were used to examine the Be-Ti and Ti-Ti interfaces in both bright field and polarized light.

F. Results and Discussion - Powder-powder composites - The mechanical properties of the powder-powder composites (Table 6) are extremely low and highly variable. Material "E" (P-1 chip Be) showed a low proportional limit of 12 ksi, modulus of 22×10^6 psi but did exhibit some ductility and a stress for first debond of ≈ 85 ksi.³

In comparison, material "F" (HP-40 chip Be) also showed a low p.l. of 16 ksi, modulus of 18×10^6 psi and virtually zero ductility. The reason for this is believed to be the extensive void formation at the ends of the Ti stringers coupled with the inherent brittleness of HP-40 type material. The differences between the two materials are apparent in Figs. 6 and 7. In

³Throughout this report the tensile values of importance are considered to be:

- a) the proportional limit, p.l.
- b) the initial elastic modulus
- c) the stress and strain to first evidence of debonding
- d) where present, the values of the 2nd modulus line
- e) also reported are values of the tensile yield strength at .01, .1 and .2% offset, the tensile strength and the total elongation.

Figure 6, the high purity Be (material E) is completely recrystallized to a relatively large grain size while the HP-40 (material F) is predominantly cold worked. It also can be seen in these figures that the Ti in material E appears to be becoming a continuous phase while this is not the case for material F. This suggests that although it was not possible to re-extrude these materials 2:1 at 425°C (800°F), improved properties might be obtained by re-extruding material E at a higher temperature and reduction ratio. With the exception of this possibility, powder-powder composites do not appear attractive.

Filamentary composites. In contrast to the powder-powder composites the mechanical properties of the filamentary composites are relatively high and more consistent, although there are significant variations between materials.

Mechanical properties (Table 7) of seven filament bundles were determined even though the reduced section contained only a single Be filament surrounded by Ti alloy. Coincidentally, the "volume percent" Be in the reduced section was about 42%; not greatly different from the 43-45% measured on the full 133 and 259 filament composites. With the exception of -400 mesh P-1 Be (material A), a p.l. ≥ 40 ksi and a modulus of about 20×10^6 psi were obtained. The stress at first debond varied from 70 to 100 ksi, about the same as powder-powder material E.

Properties (Tables 8-13) of the 133 and 259 filament materials were measured using two different specimen sizes and two different strain measurement techniques. These differences do cause some variation in the reported results. For example, the clip-on extensometer generally shows variation in Young's Modulus with a range of 17 to 32×10^6 psi. In contrast, the bonded strain gages result in a much more accurate measurement of the modulus. The actual value achieved, 28.2×10^6 psi (Table 10), is almost exactly that pre-

dicted by the rule of mixtures for 45 volume percent Be with a Be modulus of 42×10^6 psi and a Ti modulus of 16.8×10^6 psi.

There is an interesting flow curve generated by these materials. That is, after loading on the composite modulus of 28×10^6 psi, and yielding, a second "elastic" flow curve is generated in those materials exhibiting good bonding. The slope of this line or "second" modulus is about 10×10^6 psi. This can be explained in the following manner. The Be, being weaker than the Ti alloy, yields plastically while the Ti alloy is still in the elastic state. Thus, after the Be yields, a "second" modulus of about 9.2×10^6 psi is predicted when the Ti modulus of 16.8×10^6 psi is corrected for volume fraction.

Of the four materials tested, materials "B" (HIP-50), "C" (HIP-70) and "D" (HP-40) achieved a p.l. ≥ 40 ksi (Table 8). However, material "D" had virtually nil ductility as the stress for first debond was almost exactly the same as the p.l. Material "B" showed extremely erratic results with many specimens showing debonding at stresses only slightly above the p.l. and consequently exhibited little ductility. Only material "C" extruded at 650°C had the required combination of high proportional limit, debond strength and adequate ductility. Samples of this material extruded at 650°C and 705°C were tested in tension at 315°C (600°F) with the results shown in Table 13. No obvious debonding was observed so the strength and ductility reported are the conventional tensile strength and elongation in 1 inch. The high p.l. and modulus appear to be retained at this temperature.

All three materials "B", "C", "D" developed a 40 ksi p.l. for at least one of the extrusion conditions evaluated; however, only material "C" combined that with consistently high debond strengths. The relative differences in the Be-Ti interfaces of materials "C" and "D" can be seen in Figures 8

and 9 where the interface with material "C" can be seen to have much less porosity or debond area than material "D". This difference is believed to be the reason for the "early" debonding in material "D" and for the relatively high stress required for debonding of material "C".

Although material "C" is clearly the material of choice, it can be seen that all three high purity grades have exceptionally good properties if conventional tensile yield strengths are measured (Tables 11 & 12). In this case material "C" is still clearly the material of choice as is the lower extrusion temperature as tensile yield strengths (0.1% offset) of 48-58 ksi, 62 ksi and 64-69 ksi were achieved in the three materials. Note that in Table 12 where average test results are given for .01% offset, material "C" is still the choice.

At the request of NASC, an experiment was conducted to determine the feasibility of bonding a 100% dense Ti plug with the Be-Ti composite. During the final extrusion campaign a plug was inserted in lieu of the steel spacer between two composites and the resulting joint examined metallographically. No bond at the butt end of the plug occurred at all. However, the nose end of the plug did bond to the butt end of the composite over a distance of about 1/4". The strength of this bond, of course, could not be determined.

Summary - A Be-Ti composite was produced having a proportional limit ≥ 40 ksi, an elastic modulus of 28×10^6 psi, and a density of 3.32 g/cc. The beryllium used was HIP 70, a new, high-strength, high-purity grade. As determined by metallographic examination, a bond between Ti-6-4 alloy and Be-Ti composite was formed during extrusion.

Table 1
CHEMICAL COMPOSITIONS OF Be MATERIALS

			Phase I			
			Billet 76035 Mat. A	Billet 76036 Mat. B	Billet 77002 Mat. C	Billet 840W Mat. D
BeO	%	*	.86	1.61	1.59	4.59
C	%	Θ	.015	.020	.02	.086
Fe	ppm	†	275	500	400	2230
Al	"	†	75	75	50	305
Mg	"		5	5	10	35
Ni	"		110	110	170	-
Mn	"		20	20	70	-
Cr	"		15	20	55	-
Ca	"		<200	<200	<200	-
Co	"		<5	<5	<5	-
Cu	"		25	25	25	-
Zr	"		<100	<100	<100	-
Ag	"		<1	<1	1	-
Pb	"		1	<1	1	-
Si	"	Ψ	30	30	1	300
Mo	"		<10	<10	<10	-
Ti	"		<10	<10	<10	-

			Phase II	
			P-1 Chip After Screening (-35+100 mesh) Mat. E	HP-40 Chip After Screening (-35+100 mesh) Mat. 5
BeO	%	*	.07	4.35
C	%	Θ	.012	.105
Fe	ppm	†	200	2360
Al	"	†	<20	265
Mg	"		4	45
Ni	"		39	230
Mn	"		5	60
Cr	"		13	120
Ca	"		<200	<200
Co	"		<5	<5
Cu	"		-	-
Zr	"		<100	<100
Ag	"		<1	<1
Pb	"		<1	<1
Si	"	Ψ	24	700
Mo	"		<10	<10
Ti	"		<10	70

*Br-M, ΘConductometric, †Atomic Absorption, ΨWet Chemistry, All others spectrographic

Table 2

MECHANICAL PROPERTIES OF STARTING Be BILLETS

<u>Billet</u>	<u>Condition</u>	<u>T.S.</u> <u>(ksi)</u>	<u>Y.S.*</u> <u>(ksi)</u>	<u>e</u> <u>%</u>	<u>#</u> <u>Tests</u>	<u>Notes</u>
76046	As HIP L's	64.1	36.3	4.6	3	Mat. A
	As HIP T's	66.1	36.4	5.9	3	
76047	As HIP T's	85.7	60.5	5.9	3	Mat. B
77002	As HIP L's	88.6	68.5	3.8	3	Mat. C
	As HIP T's	88.8	68.4	3.6	3	

*0.2% offset yield strength

Table 3

CHEMICAL COMPOSITIONS OF TI-ALLOY MATERIALS

	<u>Tube</u> <u>Heat D5013*</u>	<u>-35+325 mesh R.E.P. Powder**</u> <u>Heat 303 999 #4252</u>
Al %	6.2	6.3
V %	4.04	4.2
Fe %	.18	.15
C %	.028	.025
H ₂ %	.0022	.005
O ₂ %	.18	.18
N ₂ %	Bal.	Bal.

*Data supplied by Oregon Metallurgical Corp.

**Data supplied by Nuclear Metals Inc.

Table 4a

EXTRUSION CONSTANTS FOR CAMPAIGN 1*

<u>Billet</u>	<u>Be Mat.</u>	<u>Load (upset) (Tons)</u>	<u>K (upset) (tsi)</u>	<u>Load (run) (Tons)</u>	<u>K (run) (tsi)</u>
76046	A	1620	32.2	1470	29.2
76047	B	1720	34.2	1490	29.6
77002	C	1680	33.4	1595	31.7
76045	D	1750	34.7	1540	30.6
76031	E	1720	34.2	1300	25.8
76032	E	1660	33.0	1190	23.6
76033	F	1750	>34.7	STALLED	
76034	F	1750	>34.7	STALLED	
76033-1**	F	1655	38.4	1280	29.7
76034-1**	F	1625	37.7	1530	35.5

*Reduction ratio 13:1 except where noted - Temp. 705°C

**Reduction ratio 9:1

Table 4b

EXTRUSION CONSTANTS FOR CAMPAIGN 2*

<u>Billet</u>	<u>Be Mat.</u>	<u>Load (upset) (Tons)</u>	<u>K (upset) (tsi)</u>	<u>Load (run) (Tons)</u>	<u>K (run) (tsi)</u>
76046-A	A	1690	33.5	1375	27.3
76046-B	A	1750	34.7	1375	27.3
76047-A	B	1750	34.7	1690	33.5
76047-B	B	1750	34.7	1690	33.5
77002-A	C	1660	33.0	1410	28.0
77002-B	C	1590	31.6	1380	27.4
76045-A	D	1605	31.9	1405	27.9
76045-B	D	1725	34.3	1695	33.6

*Reduction ratio 13:1 - Temp. 705°C

Table 4c

EXTRUSION CONSTANTS FOR CAMPAIGN 3*

<u>Billet</u>	<u>Be Mat.</u>	<u>Load (upset) (Tons)</u>	<u>K (upset) (tsi)</u>	<u>Load (run) (Tons)</u>	<u>K (run) (tsi)</u>
76046-A	A	1750	34.7	1640	32.6
76046-B	A	1660	33.0	1500	29.8
76047-A	B	1680	33.4	1620	32.2
76047-B**	B	1720	30.9	1750	31.4
77002-A	C	1570	31.2	1375	27.3
77002-B	C	1700	33.8	1445	28.7
76045	D	1750	34.7	1640	32.6

*Reduction ratio 13:1 except where noted - Temp. 705°C

**Reduction ratio 17:1 - collapsed die and stalled press at end of push

Table 4d

EXTRUSION CONSTANTS FOR CAMPAIGN 4*

<u>Billet</u>	<u>Be Mat.</u>	<u>Temp. °C</u>	<u># Fil.</u>	<u>Load (upset) (Tons)</u>	<u>K (upset) (tsi)</u>	<u>K (run) (Tons)</u>	<u>K (run) (tsi)</u>
76046-1	A	535	133	1750	>34.7	STALLED	-
76046-2	A	650	133	1630	32.3	1380	27.3
76046-3	A	705	133	1500	29.8	1250	24.8
76046-4	A	650	259	1750	34.7	1630	32.3
76046-5	A	705	259	1690	33.5	1630	32.3
76047-2	B	650	133	1750	34.7	STALLED	-
76047-3	B	705	133	1590	31.6	1440	28.5
76047-4	B	650	259	1720	34.1	1630	32.3
76047-5	B	705	259	1690	33.5	1440	28.5
76048-2	C	650	133	1750	34.7	1590	31.6
76048-3	C	705	133	1350	26.7	940	18.6
76048-4	C	650	259	1750	34.7	1560	30.9
76048-5	C	750	259	1720	34.1	1590	31.6
76045	D	750	133	1720	34.1	1590	31.6

*Reduction ratio 13:1

Table 5

DENSITIES OF FILAMENTARY COMPOSITES

<u>Material</u>	<u>Density (g/cc)</u>
A-133	3.331
"	3.388
A-259	3.291
"	3.324
"	3.263
"	3.325
B-133	3.354
B-259	3.303
"	3.325
"	3.291
"	3.296
C-133	3.245
"	3.341

Table 6

MECHANICAL PROPERTIES OF POWDER-POWDER COMPOSITES

<u>Material</u>	<u>Proportional Limit & Range (ksi)</u>	<u>Initial Modulus & Range (10⁶ psi)</u>	<u>Stress at 1st Debond & Range (ksi)</u>	<u>Strain to 1st Debond (%)</u>	<u># Tests</u>
"E"	12.6(8-16)	22.2(21-24)	85(65-125)	≈.9	4
"F"	15.6(6-22)	18.2(11-22)	17(6-22)	≈.1	4

"Large" tensile specimen (1/4" gage dia., 1/2" gage length). P.L. and modulus determined from load extension curve generated by clip-on extensometer at a magnification ratio of 500:1.

Table 7

MECHANICAL PROPERTIES OF 7 FILAMENT* BUNDLES

<u>Material</u>	<u>Proportional Limit & Range (ksi)</u>	<u>Initial Modulus & Range (10⁶ psi)</u>	<u>Stress at 1st Debond & Range (ksi)</u>	<u>Strain to 1st Debond (%)</u>	<u># Tests</u>
"A"	34.9 (32-38)	14.4 (12-18)	70 (55-92)	≈.6	4
"B"	46.5 (41-55)	21.4 (18-24)	68 (47-107)	≈.3	4
"C"	40.5 (35-45)	19.0 (16-21)	89 (60-107)	≈.6	4
"D"	43.2 (42-44)	23.0 (20-26)	100 (80-120)	≈.6	2

Extruded 3X, standard "mini" tensile (1/8" gage dia., 1/2" gage length).

*Actual specimen has single Be filament approximately .080" dia. with .020" titanium alloy cladding. P.L. and modulus determined from load-extension curve generated by clip-on extensometer at a magnification ratio of 1000:1.

Table 8

MECHANICAL PROPERTIES OF 133 AND 259 FILAMENT COMPOSITES

Material # Fil.	Ext. Temp °C	Proportional Limit & Range (ksi)	Initial Modulus & Range (10 ⁶ psi)	Stress at 1st Debond & Range (ksi)	Strain to 1st Debond (%)	# Tests
A-133	650	29.6 (29-30)	25.8 (22-31)	169 (167-171)	2.0	3
A-133	705	22.9 (19-28)	26.8 (25-28)	153 (152-154)	2.2	3
A-259	650	23.9 (20-28)	32.3 (27-37)	157 (155-158)	2.1	3
A-259	705	7.6 (5-10)	17.3 (15-20)	149 (146-155)	2.1	2
B-133	705	40.3 (36-46)	29.2 (26-33)	52 (48-56)	0.2	3
B-259	650	41.8 (41-44)	20.9 (19-22)	124 (50-162)	0.3-2.2	3
B-259	705	32.6 (30-35)	22.1 (18-26)	88 (52-154)	0.3-2.1	3
C-133	650	35.7 (32-41)	24.2 (18-33)	128 (113-147)	1.0	3
C-133	705	27.8 (19-36)	22.4 (21-24)	157 (156-158)	3.5	3
C-259	650	40.3 (35-45)	26.0 (23-34)	167 (149-175)	1.8	6
C-259	705	25.8 (17-31)	26.9 (20-36)	160 (145-170)	1.8	3
D-133	705	50.3 (49-51)	24.8 (24-26)	53 (49-60)	0.2	3

Standard "mini" specimen (1/8" gage dia., 1/2" gage length). P.L. and modulus measured from load-extension curve generated by a clip-on extensometer at a 1000:1 magnification ratio.

Table 9

EFFECT OF SPECIMEN SIZE AND STRAIN MEASUREMENT
TECHNIQUE ON OBSERVED PROPERTIES

<u>Material</u>	<u>Ext. Temp °C</u>	<u>P.L. (ksi)</u>	<u>Initial Modulus (10⁶ psi)</u>	<u>2nd Modulus (10⁶ psi)</u>	<u>Stress at 1st Debond (ksi)</u>	<u>Specimen Type* & Gaging</u>
A-133	650	29.6	25.8	11.8	169	S-ext.
A-259	650	23.9	32.3	10.9	157	S-ext.
A-259	650	18.6	28.4	-	152	L-s.g.
A-133	705	22.9	26.8	10.9	153	S-ext.
A-259	705	7.6	17.3	10.2	149	S-ext.
A-259	705	16.6	29.1	-	119	L-s.g.
B-133	705	40.3	29.2	-	52	S-ext.
B-259	705	32.6	22.1	-	88	S-ext.
B-259	705	17.5	28.1	-	43	L-s.g.
B-259	650	41.8	20.9	10.7	124	S-ext.
B-259	650	18.3	28.9	-	56	L-s.g.
C-133	650	35.7	24.2	10.3	128	S-ext.
C-259	650	40.3	26.0	10.1	167	S-ext.
C-259	650	39.3	29.4	-	139	L-s.g.
C-259	650	26.4	29.9	9.7	105	L-ext.
C-133	705	27.8	22.4	9.9	157	S-ext.
C-259	705	25.8	26.9	10.5	160	S-ext.
C-259	705	18.0	28.3	-	132	L-s.g.
C-259	705	24.0	30.0	10.3	130	L-ext.

*S - 1/8" Ø x 1/2" gage length
 L - 1/4" Ø x 1" gage length
 ext. - clip on extensometer
 s.g. - bonded strain gage

Table 10

YOUNG'S MODULUS (10^6 psi) OF 259 FILAMENT COMPOSITES

Material	Ext. Temp °C	Test #				Average
		1	2	3	4	
"A"	650	28.1	28.3	28.0	28.5	28.2
"A"	705	29.1	29.1	29.4	-	29.2
"B"	650	29.1	29.2	29.8	29.4	29.4
"B"	705	28.3	28.3	28.3	-	28.3
"C"	650	28.1	28.2	28.3	28.1	28.2
		28.5	27.9	28.3	28.2	28.2
"C"	705	28.2	28.4	28.1	-	28.2

Specimen (1/4" gage diameter, 1" gage length)-measured from load-strain curves generated by a full bridge bonded strain gage over the stress range 0-4000 psi and strain range of $0-150 \times 10^{-6}$.

Table 11

CONVENTIONAL MECHANICAL PROPERTIES OF 133 AND 259 FILAMENT COMPOSITES

Material # Fil.	Ext. Temp. °C	Tensile Yield Stress (.1% offset) ksi	Tensile Yield Stress (.2% offset) ksi	Tensile Strength ksi	Elong. %
A-133	650	58.0	79.8	169.8	3.8
A-133	705	56.1	86.0	153.2	2.5
A-259	650	48.6 (48.0)	65.0	156.6	2.9
A-259	705	38.1 (40.6)	61.0	149.5	4.3
B-133	705	56.3	59.1	148.9	1.9
B-259	650	62.3 (61.2)	78.9	160.9	2.5
B-259	705	52.1 (49.1)	66.4	148.6	1.9
C-133	650	69.4	87.8	149.4	1.2
C-133	705	54.6	73.1	157.1	6.3
C-259	650	67.3 (64.3)	82.8	169.3	2.2
C-259	705	64.7 (55.9)	77.2	163.2	2.8
D-133	705	-	-	130.1	2.4

Standard "mini" specimen (1/8" gage diam., 1/2" gage length).

Tensile yield strengths measured from load-extension curve generated by a clip-on extensometer at a 1000:1 magnification ratio. Values in parentheses were measured on "large" specimens (1/4" gage diam., 1" gage length) using bonded strain gages.

Table 12

TENSILE YIELD STRESS (.01% offset)

<u>Material # Fil.</u>	<u>Ext. Temp. °C</u>	<u>Yield Stress and Range (ksi)</u>	<u>No. Tests</u>
A-133	650	35.6 (34-39)	3
A-133	705	28.6 (25-33)	3
A-259	650	33.3 (28-38)	4
A-259	705	18.5 (10-30)	3
B-133	705	47.9 (45-51)	3
B-259	650	47.3 (46-49)	4
B-259	705	39.7 (38-41)	4
C-133	650	48.0 (45-51)	3
C-133	705	27.6 (11-43)	3
C-259	650	50.4 (45-56)	10
C-259	705	38.9 (36-42)	3
D-133	705	*-	3

*First debond occurred at less than .01% strain

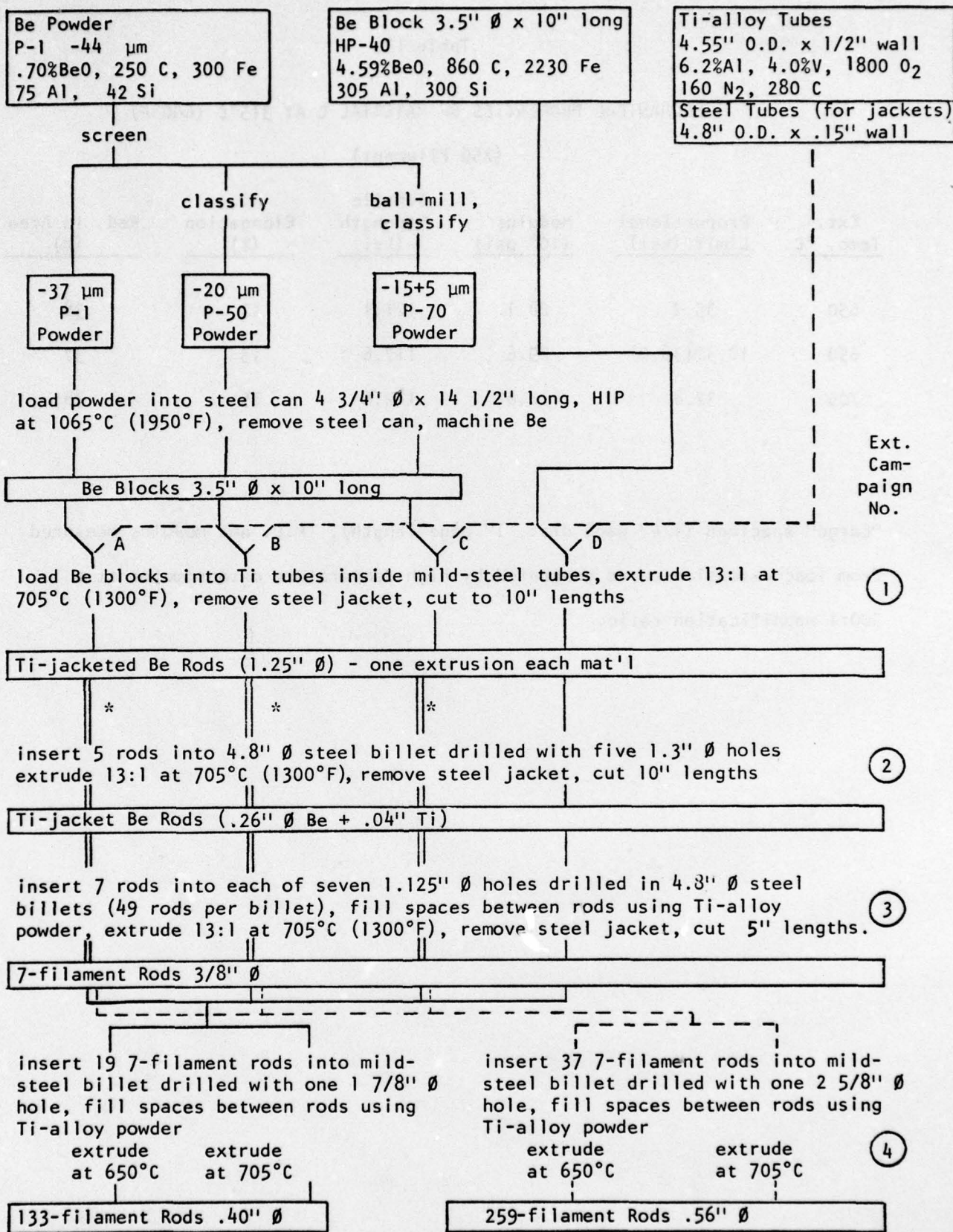
Table 13

MECHANICAL PROPERTIES OF MATERIAL C AT 315°C (600°F)

(259 Filament)

<u>Ext. Temp. °C</u>	<u>Proportional Limit (ksi)</u>	<u>Modulus (10⁶ psi)</u>	<u>Tensile Strength (ksi)</u>	<u>Elongation (%)</u>	<u>Red. in Area (%)</u>
650	35.2	28.1	121.1	11	38
650	10.37(36.0)	29.6	117.6	13	37
705	32.8	12.67	112.6	15	38

"Large" specimen (1/4" gage dia., 1" gage length). P.L. and modulus measured from load-extension curve generated by high temperature extensometer at a 500:1 magnification ratio.



*2 billets of materials A, B and C were extruded.

Fig. 1. Phase I program for producing filamentary Be/Ti alloy composite rods.

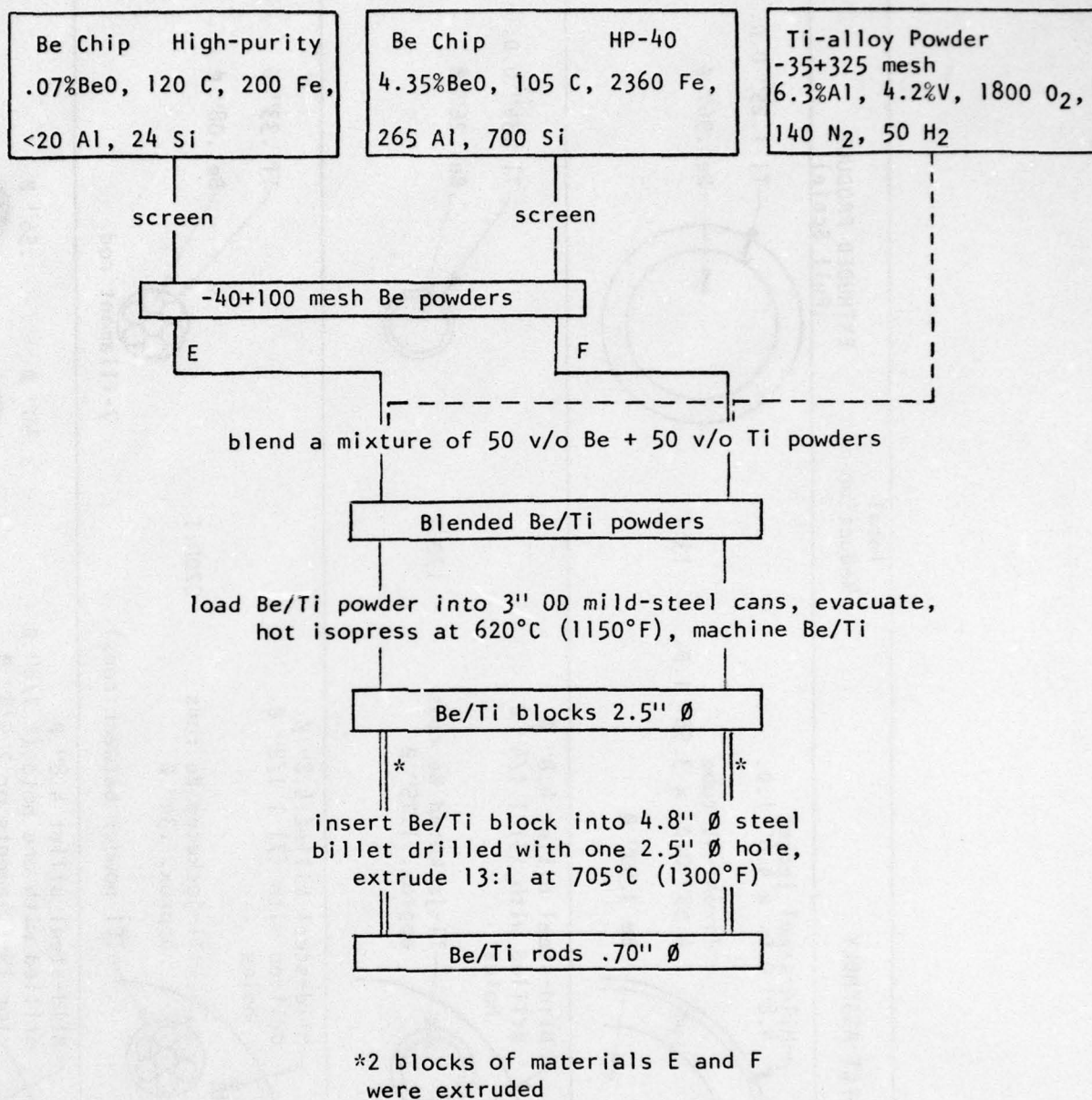


Fig. 2. Phase II program for producing powder/powder Be/Ti-alloy composite rods.

Extrusion Campaign No.	EXTRUSION BILLET ASSEMBLY	Total Reduction	EXTRUDED PRODUCT (Full Scale)
1	<p>Mild-steel jacket 4.8" O.D. x 4.6" I.D.</p> <p>Ti-6Al-4V tube 4.55" O.D. x 3.55" I.D.</p> <p>Be 3.50" ϕ</p>	13:1	<p>Ti 1.25" O.D.</p> <p>Be .96" ϕ</p>
2	<p>Mild-steel billet 4.8" ϕ drilled with (5) 1 1/4" holes</p> <p>Ti-jacketed Be rods approx. 1.25" ϕ</p>	170:1	<p>Ti .34" O.D.</p> <p>Be .26" ϕ</p>
3	<p>Mild-steel billet 4.8" ϕ drilled with (7) 1 1/8" holes</p> <p>Ti-jacketed Be rods approx. .34" ϕ</p> <p>(Ti powder between rods)</p>	2200:1	<p>Ti .33" ϕ</p> <p>Be .08" ϕ</p> <p>7-filament rod</p>
4	<p>Mild-steel billet 4.8" ϕ drilled with one hole (1 7/8" ϕ for 19-filaments or 2 5/8" ϕ for 37-filaments)</p> <p>Bundle of 19 or 37 7-filament rods</p>	28500:1	<p>.40" ϕ</p> <p>.56" ϕ</p> <p>133 filament rod</p> <p>259 filament rod</p> <p>Be .02" ϕ</p>

Fig. 3 Phase I extrusions. Reduction ratio for each extrusion was 13:1. Campaign numbers correspond to those shown in Fig. 1. See Fig. 1 for extrusion temperatures, etc.

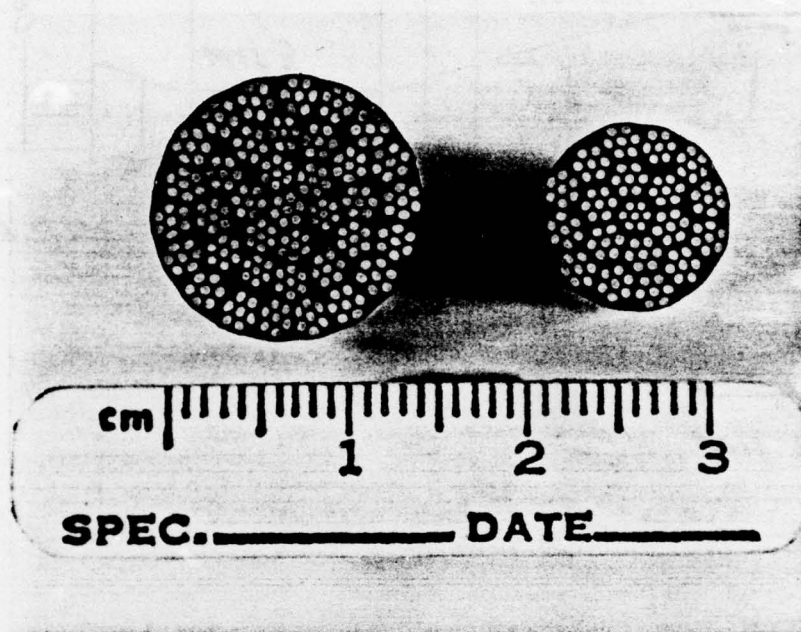
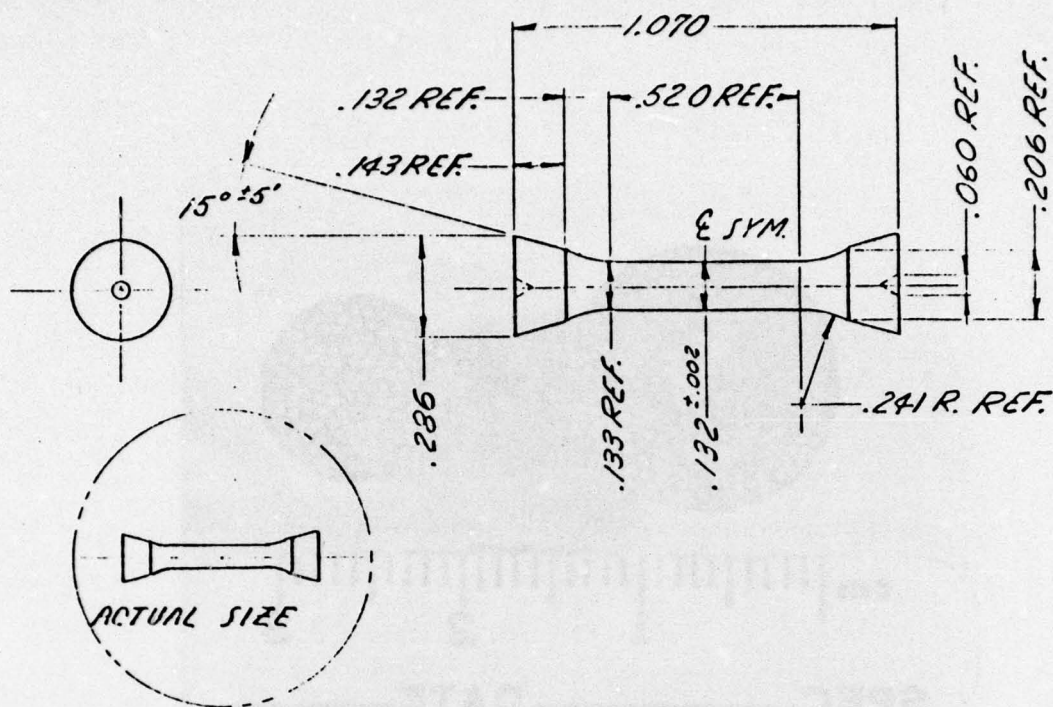


Fig. 4. Be-Ti filamentary composites (259 and 133 filaments) produced. Approx. 2.5X.



NOTES:

1. FILLET RADII MUST BE TANGENT; NO UNDERCUT.
2. REDUCED SECTION HAS A GRADUAL TAPER FROM THE ENDS TOWARD THE CENTER WITH THE ENDS .001-.0015 LARGER IN DIAMETER THAN THE CENTER.
3. HOLD SYMMETRICAL WITH RESPECT TO ENDS REGARDLESS OF LENGTH DIMENSIONS.
4. ETCH .003-.004 PER SURFACE BEFORE TESTING.

Fig. 5. Standard Mini bar tensile specimen.

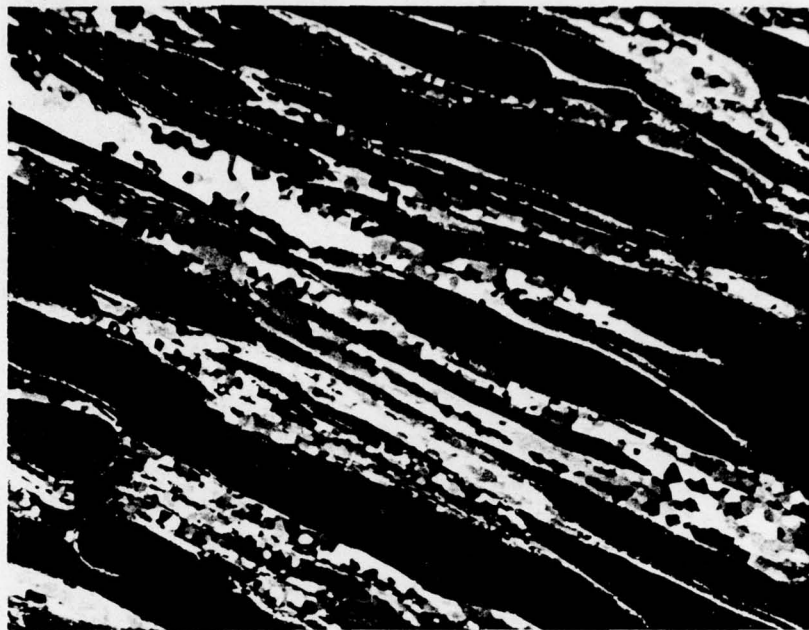


Fig. 6. Powder-powder composite with high purity Be. Pol. light 100X.

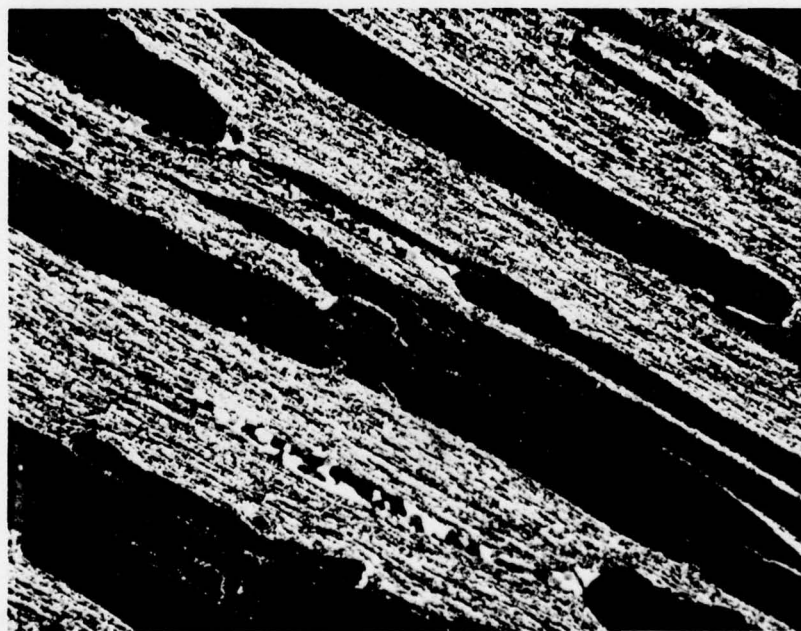
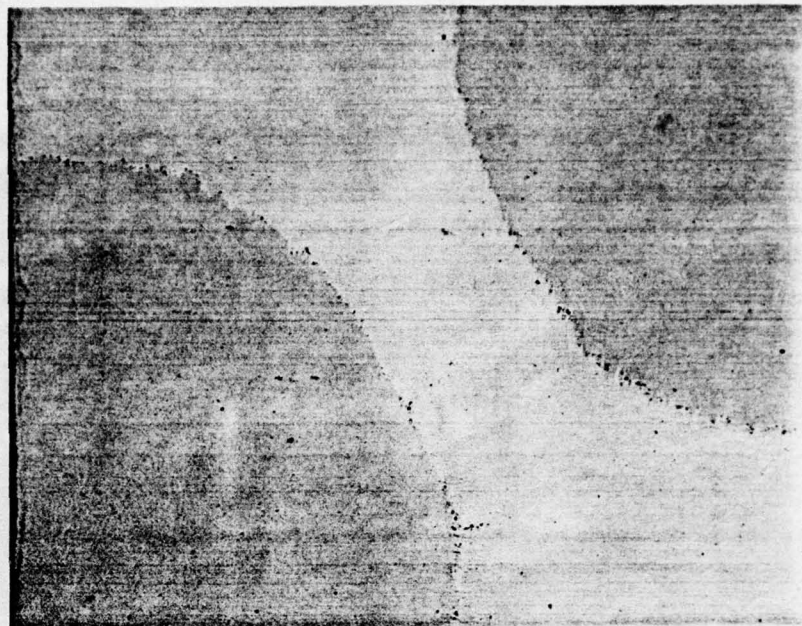
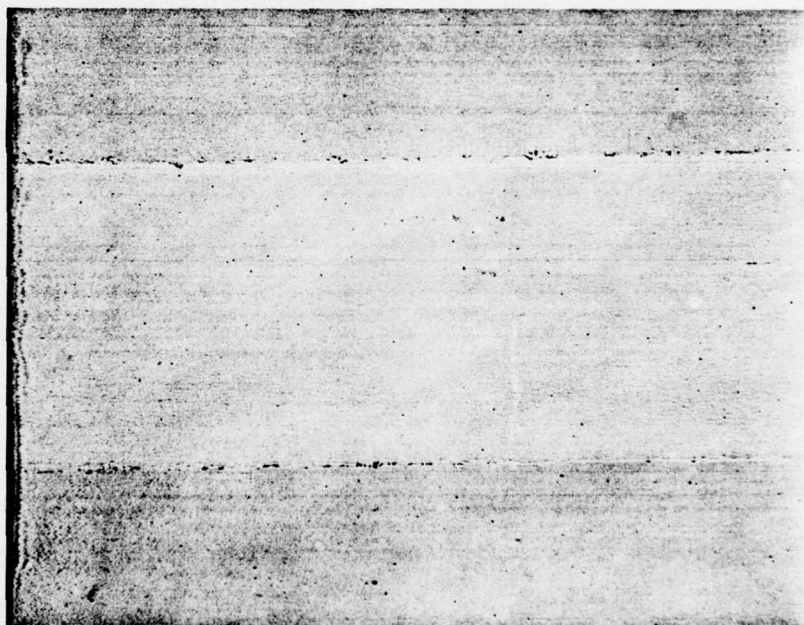


Fig. 7. Powder-powder composite with HP-40 type Be. Pol. light 100X.

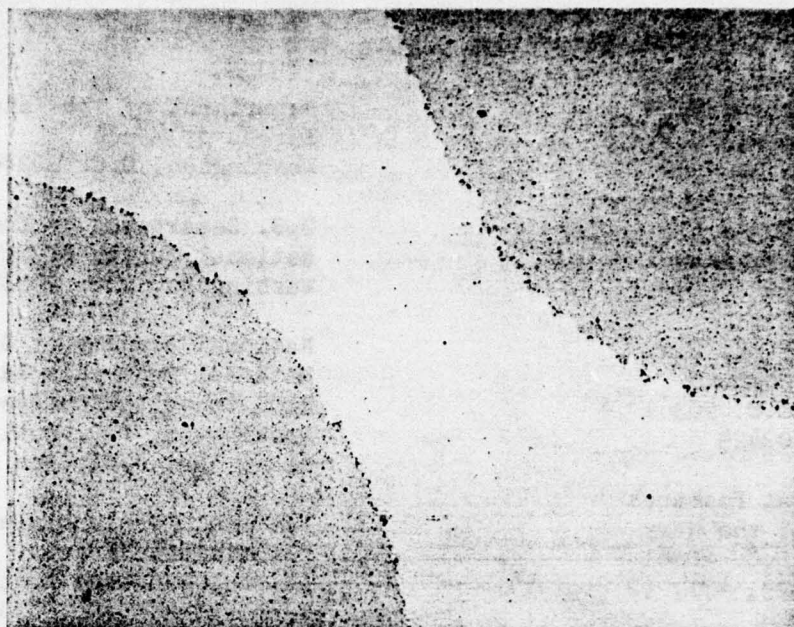


(a)

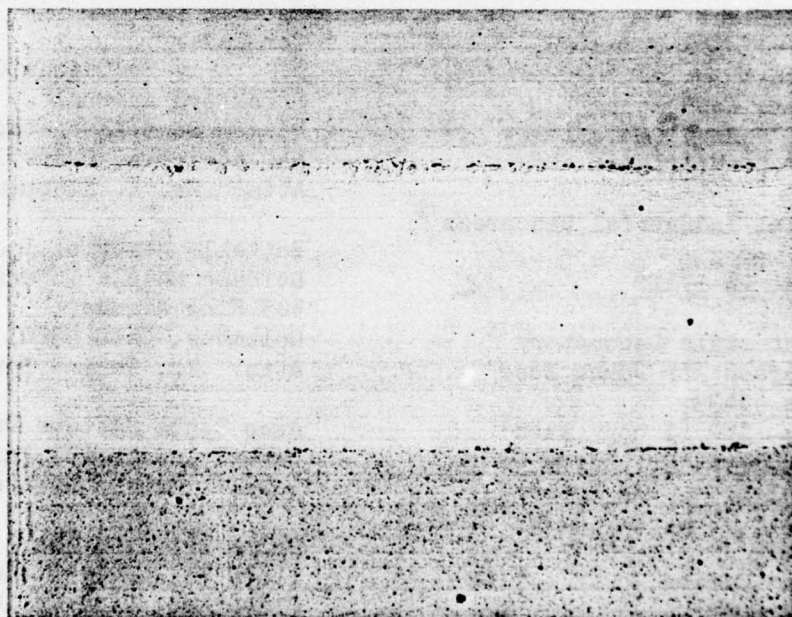


(b)

Fig. 8. Be-Ti interface in material C. (a) Transverse, (b) Longitudinal. 200X.



(a)



(b)

Fig. 9. Be-Ti interface in material D. (a) Transverse, (b) Longitudinal. 200X.

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